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MIXING AND CP VIOLATION IN D MESONS

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Résumé

Nous examinons le mélange et la violation de CP dans les mésons D d'après le Modèle Standard, en soulignant les différences avec les autres mésons pseudo-scalaires, et montrons que les mésons D peuvent être utiles dans la recherche d'une nouvelle physique au-delà du Modèle Standard.

Abstract

We review mixing and CP violation in D mesons, emphasizing the differences with the other pseudoscalar mesons in the Standard Model, and show that D mesons can be useful to look for physics beyond the Standard Model.

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In the study of the weak interactions of pseudoscalar mesons, there are a number of interesting properties : i) decay rates ; ii) P^0 - \bar{P}^0 mixing, and iii) CP violation, that, if the Standard Model is correct, result from the Cabibbo-Kobayashi-Maskawa matrix. It is convenient to parametrize this matrix following the phase convention and expansion in powers of the Cabibbo angle $\lambda = \sin \theta_C = 0.22$, due to Wolfenstein¹ :

$$V \cong \begin{pmatrix} 1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1 \end{pmatrix} . \quad (1)$$

The flavor structure of the Standard Model provides several interesting pairs of neutral pseudoscalar mesons P^0 - \bar{P}^0 , as indicated in Table 1. We indicate in the Table the power counting in terms of λ of the dominant decay rates, mixing, life-time differences and CP asymmetries. It is remarkable that this complex set of properties is for the moment in quantitative agreement with the expectations of the Standard Model, as expressed by the matrix (1).

Mixing occurs through radiative corrections in the Standard Electroweak Theory (box diagrams). The mass eigenstates are :

$$|P_{1,2} \rangle = p|P^0 \rangle \pm q|\bar{P}^0 \rangle . \quad (2)$$

This mixing produces $P^0 \leftrightarrow \bar{P}^0$ oscillations of amplitude $e^{i\Delta Mt}$. The parameter controlling the oscillations is $\Delta M/\Gamma$, given for the different systems in Table 1, where we also give $\Delta\Gamma/\Gamma$.

Concerning CP violation, the unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix implies, for the different systems, triangular relations among CKM matrix elements. These relations define triangles in the complex plane that are of equal surface $S = A\lambda^6\eta$ (due to the fact that there is a single complex phase in the CKM matrix) but of different shapes according to the considered system (Table 1). The CP asymmetries are roughly proportional to the ratio Surface of unitarity triangle/Rate of the considered mode. It is remarkable that the simple power counting gives the right order of magnitude for the mixing parameters (within the present experimental limits for D^0 - \bar{D}^0 and B_s^0 - \bar{B}_s^0) and for the kaon CP violation parameter $|\varepsilon| \sim 10^{-3}$.

Table 1

	K^0 - $\bar{K}^0(\bar{s}d - s\bar{d})$	D^0 - $\bar{D}^0(\bar{u}c - c\bar{u})$	B_d^0 - $\bar{B}_d^0(\bar{b}d - b\bar{d})$	B_s^0 - $\bar{B}_s^0(\bar{b}s - b\bar{s})$
Rates	λ^2	1	λ^4	λ^4
$\frac{\Delta M}{\Gamma}$	m_c^2 $\tau\Delta M \cong 0.5$	$\lambda^2 m_s^2$ $\tau\Delta M < 0.08$	$\lambda^2 m_t^2$ $\tau\Delta M \cong 0.7$	m_t^2 $\tau\Delta M > 9$
$\frac{\Delta\Gamma}{\Gamma}$	1 $\Gamma_S \gg \Gamma_L$	λ^2 $\tau\Delta\Gamma < 0.17$	λ^2	1
Unitarity triangles	$\sum_U V_{Ud}V_{Us}^* = 0$	$\sum_D V_{Du}V_{Dc}^* = 0$	$\sum_U V_{Ud}V_{Ub}^* = 0$	$\sum_U V_{Us}V_{Ub}^* = 0$
Surface of triangles	$A^2\lambda^6\eta$	$A^2\lambda^6\eta$	$A^2\lambda^6\eta$	$A^2\lambda^6\eta$
CP Asym. $\sim \frac{\text{Surface}\Delta}{\Gamma(\text{mode})}$	$\lambda^4\eta$ $ \varepsilon \sim 10^{-3}$	$\lambda^6\eta$	$\lambda^2\eta$	$\lambda^2\eta$

1 D^0 - \bar{D}^0 mixing

Charged D^* decays can be used to identify the flavor of the neutral D by observing the pion charge : $D^{*+} \rightarrow D^0\pi^+$, $D^{*-} \rightarrow \bar{D}^0\pi^-$. Looking for the time dependence in the decay can help to separate² the process due to mixing $D^0 \rightarrow \bar{D}^0 \rightarrow K^+\pi^-$ from the doubly Cabibbo suppressed decay (DCSD) $D^0 \rightarrow K^+\pi^-$. The time dependence of the rate is, for small time :

$$R(D^0 \rightarrow K^+\pi^-) \sim e^{-\Gamma t} \left[|\rho_{DCS}|^2 + \frac{1}{2}(x^2 + y^2)t^2 + \dots \right] \quad (3)$$

where $x = \Delta M/\Gamma$, $y = \Delta\Gamma/2\Gamma$ and ρ_{DCS} stands for the amplitude of the doubly Cabibbo suppressed mode. The present limits obtained with this method are given in Table 1.

As for the theory, the short distance box diagram (with the b quark in the loop) is highly suppressed by powers of λ , and gives

$$\left(\frac{\Delta M}{\Gamma} \right)_{\text{short distances}} \sim 3 \times 10^{-5} \quad . \quad (4)$$

However, as pointed out by Wolfenstein³, there are long distance contributions, real intermediate states of the type :

$$D^0 \rightarrow K\bar{K}, \pi\pi, \pi K, \pi\bar{K} \rightarrow \bar{D}^0 \quad . \quad (5)$$

This sum vanishes in the exact SU(3) limit because of the GIM mechanism. However, for some individual modes, SU(3) is badly broken, like $\Gamma(K\bar{K}) \sim 3 \times \Gamma(\pi\pi)$, and Wolfenstein claims, as an order of magnitude, $(\Delta M/\Gamma)_{\text{long distances}} \sim (\Delta\Gamma/\Gamma)_{\text{long distances}} \sim 0.01$.

However, more detailed calculations of the dispersive part $\Delta M/\Gamma$ with the intermediate states (4) by Donoghue et al.⁴ and updated by Pakvasa⁵, and also QCD symmetry arguments on the operators that can contribute to D^0 - \bar{D}^0 mixing by Georgi⁶, point rather to a much smaller result for the long distance contribution, at most of the order :

$$\left(\frac{\Delta M}{\Gamma} \right)_{\text{long distances}} \sim 10 \times \left(\frac{\Delta M}{\Gamma} \right)_{\text{short distances}} \quad . \quad (6)$$

If this estimation is the correct one, it leaves room for the search of physics beyond the Standard Model, as shown in Table 2⁵. However, at least in the case of $\Delta\Gamma/\Gamma$, it remains to be seen how Georgi symmetry arguments are realized concretely in the sum over real intermediate states, where Wolfenstein's argument seems on firm ground.

Table 2

	$\Delta M/\Gamma$
Modèle Standard	$10^{-5} - 10^{-4}$
Two Higgs model	$> 10^{-4}(\tan\beta \gg 1)$
4th generation	10^{-2}
Flavor-changing neutral Higgs	$10^{-2} - 10^{-1}$
SUSY	$10^{-5} - 10^{-4}$
L-R Symmetry	$10^{-5} - 10^{-4}$

2 CP violation

2.1 Standard Model

As we see in Table 1, the CP asymmetries are very small in the Standard Model for Cabibbo allowed D decays (naively one expects numbers of the order or smaller than 10^{-5}).

However, in Cabibbo suppressed decays like $D \rightarrow \pi\pi$, $K\bar{K}$, $K\bar{K}^*$, $\rho\pi$, ... one can have higher asymmetries from the interference between the tree amplitude, the Penguin diagram amplitude, and strong phases coming from nearby resonances. The CP asymmetries can occur because the tree amplitude ($\sim V_{ud}V_{cd}^*$) has a different phase than the Penguin diagram ($\sim V_{ub}V_{cb}^*$) coming from the operator induced by radiative corrections with the b quark in the loop :

$$-\frac{\alpha_s(\mu^2)}{12\pi} \log\left(\frac{m_b^2}{\mu^2}\right) V_{ub}V_{cb}^* [\bar{u}\gamma_\mu(1-\gamma_5)\lambda^a c] [\bar{q}\gamma_\mu\lambda^a q] \quad . \quad (7)$$

For example⁷, considering for the mode $D \rightarrow K\bar{K}^*$ there are resonances near the D mass that provide the necessary strong phases.

$$A(D \rightarrow K\bar{K}^*) = V_{ud}V_{cd}^* A_{tree} + V_{ub}V_{cb}^* A_{Penguin} \quad . \quad (8)$$

There are two isospin amplitudes $\Delta I = 1/2$ (tree and Penguin) and $\Delta I = 3/2$ (tree), resulting in an asymmetry that can occur even for charged D mesons (direct CP violation) :

$$Asym(D \rightarrow K\bar{K}^*) \sim Im(V_{ud}V_{cd}^*V_{cb}V_{ub}^*) Im[A_{3/2}(A_{1/2})^*] \quad . \quad (9)$$

One finds rather large asymmetries, of the order $Asym(K\bar{K}^*) \sim 10^{-3}$ while for other modes, the asymmetry is smaller : $Asym(K^+K^-) \sim 10^{-4}$ (the present experimental limit⁸ is $A(K^+K^-) < 0.45$).

2.2 Beyond the Standard Model

Since CP asymmetries are expected to be very small in Cabibbo allowed decays, these could be the right place to look for other possible sources of CP violation beyond the Standard Model⁹.

As an example, let us consider the decay mode $D \rightarrow \bar{K}\pi$ where we have two isospin channels, $\Delta I = 1/2$ and $\Delta I = 3/2$. The Final State Interaction phases are expected to be large because there is a nearby wide resonance $K_0^*(1950)$ coupled to these channels. On the other hand, as emphasized by Bauer, Stech and Wirbel¹⁰, one needs a large phase shift $\delta_{1/2} - \delta_{3/2} = (77 \pm 11)^\circ$ to account for the ratio $\Gamma(D^0 \rightarrow \bar{K}^0\pi^0)/\Gamma(D^0 \rightarrow K^-\pi^+)$ that otherwise would be too small.

There are no Penguins in these decays, and only the tree amplitude $\sim V_{ud}V_{cs}^*$ contributes in the Standard Model. Therefore, from the weak interaction point of view, the amplitudes $\Delta I = 1/2$ and $\Delta I = 3/2$ have the same phase, leading to a vanishing direct CP asymmetry. However, there could be a very small asymmetry from mixing by interference between the amplitudes $D^0 \rightarrow K^-\pi^+$ and $D^0 \rightarrow \bar{D}^0 \rightarrow K^-\pi^+$, leading to an asymmetry of the order $\sim 10^{-6}$.

If there is another source of CP violation beyond the Standard Model, in general the weak phases of the amplitudes $\Delta I = 1/2$ and $\Delta I = 3/2$ will be different, and we will have an asymmetry

$$\begin{aligned}
Asym(K\pi) &\sim \sin(\delta_{1/2} - \delta_{3/2}) \left[(M_{1/2}^{SM})^* M_{3/2}^{BSM} - (M_{3/2}^{SM})^* M_{1/2}^{BSM} \right] \\
&\sim 4 \times 10^{-2} \sin \varphi_{BSM} \frac{(TeV)^2}{\Lambda^2}
\end{aligned} \tag{10}$$

where φ_{BSM} is a CP phase coming from physics beyond the Standard Model. The asymmetry will test this new source of CP violation if $\sin \varphi_{BSM} \gg \lambda^4$.

To observe an asymmetry of $O(10^{-2})$ at the 3σ level one needs 10^6 $D^0 \bar{D}^0$ pairs, a number that can be reached at a Tau-Charm Factory.

However, “realistic” models of CP violation beyond the Standard Model, constrained by the kaon CP parameters ε and ε' , predict a much weaker asymmetry. For example, in the L-R symmetric model with spontaneous CP violation one expects an asymmetry $\leq 2 \times 10^{-4}$. Still, the charm sector could be enhanced by some unknown reason (Higgs couplings ?) and it is worth to look for CP violation in these modes.

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